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Tightness Assessment of Bolted Flange Connections Considering the Creep Effect of Gasket

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Abstract

The tightness of bolted flange connections is the important guarantee to meet the safety operation for a long period, the creep effect of gasket may affect the tightness of bolted flange connections under high temperature conditions due to its creep deformation. Considering the creep effect of metal flexible graphite composite gasket under high temperature, the deformation compatibility equation of bolted flange connection system was deduced. The time-dependence of flange rotation, the gasket deformation and the gasket contact stress were studied systematically. Moreover, the influencing factors of leakage rate were analyzed in detail. Finally, based on the theory of tightness, the safety assessment method due to leakage rate was constructed under high temperature. Results presented the gasket stress increases linearly from inside to outside and the gasket stress became lower and lower with the creep time extended. The time-dependent leakage rate of bolted flange connections was deduced, and the tightness assessment can be made conveniently according to the proposed method.

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Keywords: Tightness; High temperature; Flange; Creep; Leakage rate

1. Introduction

Bolted flange connection system is widely used in chemical industry, aerospace, petroleum and other industries. High temperature is the typical working environment in such fields. Under this case, the creep deformation of bolted flange system will occur, especially for the gasket. Bolted flange connection will produce a series of changes due to the creep deformation[1], such as time-dependent elongation of bolt, time-dependent deflection of flange and gasket stress. This may cause the compression residual stress of gasket drops obviously[2].When the gasket residual

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contact stress decreases that can't be able to ensure the minimum pressure of good sealing of bolted flange connection system , the whole system will generate the phenomenon of leakage[3-5].

Nomenclature

w_s	radial displacement of cylinder(mm)
w_f	radial displacement of flange body(mm)
θ_s	rotation of cylinder body(rad)
θ_f	rotation of flange body rotation(rad)
S_K	gasket initial tightening stress(MPa)
A_G	effective contact area of gasket(mm^2)
A_P	pressurized area of gasket force encircles(mm^2)
h_P	radial distance from bolt circle to PA_P (mm)
h_g	radial distance from bolt circle to gasket force(mm)
K_b	bolt uniaxial stiffness(N/m)
K_g	gasket uniaxial stiffness(N/m)
F_b	bolt force (N)
F_g	gasket force(N)
w_b	radial displacement of bolt(mm)
w_f	radial displacement of flange(mm)
P	internal pressure(MPa)
V_f	ratio of flange Poisson
g_0	thickness of the cylinder(mm)
V	influence factor of the gasket contacts(mm)
θ	rotation of flange(rad)
D_G	average diameter of the gasket contacts(mm)
D_G	average gasket deformation(mm)
D_g	gasket deformation at any radial position(mm)
L	leakage rate($cm^3 / s \cdot mm$)

Subscript

b	refers to bolt
f	refers to flange
g	refers to gasket

Superscript

i	refers to initial condition
f	refers to operating
c	refers to creep
T	relative to temperature

The tightness of the bolted flange connection system on the theoretical research and finite element analysis has been studied by many investigators. Based on the requirement of stiffness and sealing, the intensity of bolt and gasket was calculated to evaluate the sealing performance [6].It was difficult to satisfy the minimum contact stress if sealing gaskets worked for a long time, it insist the tightness only relates to the gasket stress in the bolted flange system [7], this attitude was limited on the tightness evaluation. In this paper, based on the predecessors' research, a series of action that the gasket deformation and residual stress are produced due to the flange rotation, their impact on the leakage of entire system is considered. And from inside to outside of the gasket, the deformation and compression stress increase linearly. When bolted joint components during the initial tightening phase, the contact stress must higher than the gasket initial sealing pressure, and when gasket bolted joint components during the operating phase, the residual stress must be higher than the minimum gasket compression stress in order to guarantee the seal of gasket. On the basis of these phenomenons, the time-dependent gasket stress and leakage rate can be verified, so the assessment of the whole system is identified.

2. Rotation calculation

As shown in Fig. 1 and Fig. 2, the WN-welding neck flange and the metal flexible graphite composite gasket are used in the thesis. Flange is divided into three parts namely the cylinder, the cone, and the flange ring, for the convenience of calculating, the hub and the flange ring are deemed to be a whole. According to the principle of deformation compatibility, the flange rotation and radial displacement in the joint of these two parts are equal. The equations are given: $w_s = w_f$, $\theta_s = \theta_f$;and this two parts could be influenced by the discontinuous edge moment M_0 and the discontinuous edge force P_0.At the same time, under the condition of initial tightening, bolt force F_b^i , gasket force F_g^i and bending moment M_f^i act on the flange, making the whole system meet the requirements of seal.

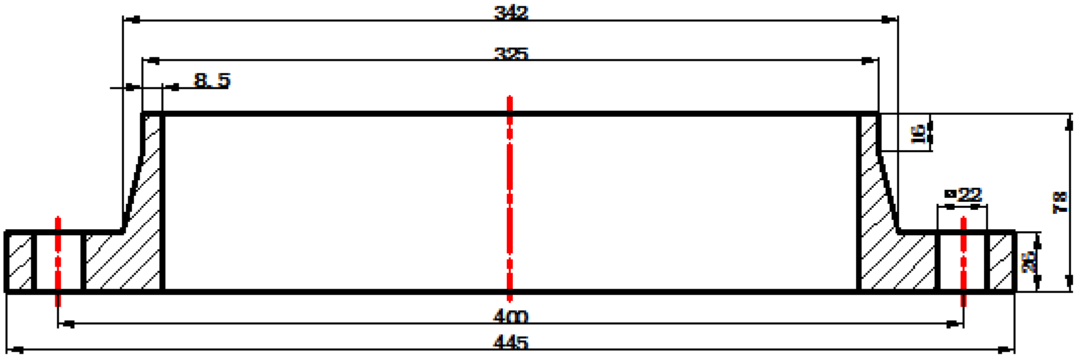

Fig. 1. Welding neck flange.

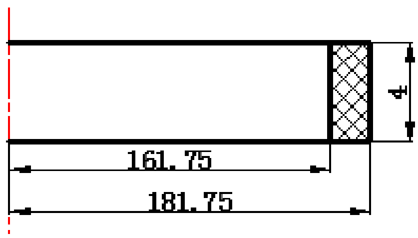

Fig. 2. Flexible graphite composite gasket.

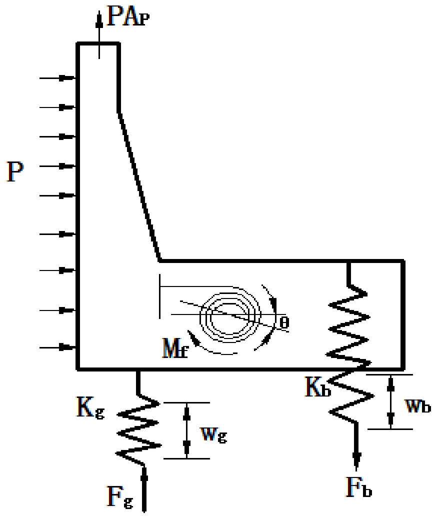

Fig. 3. Bolted flange connection system.

Under the condition of operating, except of the bolts force F_b^f ,gasket force F_g^f and bending moment M_f^f ,the flange will also be affected by the force PA_P that is generated by the internal pressure[8].

As it is shown in Fig. 3,the balance equation can be obtained:

$$M_f^i = S_K A_G h_g \tag{1}$$

In the conditions of operating, the bending moment of the flange:

$$M_f^f = PA_P h_P + F_g^f h_g \tag{2}$$

S_K is the gasket initial tightening stress, taking the S_K to 40MPa,60MPa and 80MPa.

The balance equation of force is:

$$F_b^i = F_g^i \tag{3}$$

$$F_b^f = F_g^f + PA_P \tag{4}$$

The flange rotation is mainly made up of the rotation under the function of internal medium pressure, bending moment and bolt initial tightening force, and the flange structure is divided into the cylinder and the flange body. According to the principle of deformation compatibility, the rotation of these two parts in the joint is equal, regarding the cylindrical wall as thin, discontinuous edge bending moment and discontinuous edge pressure(ignoring the impact of temperature)are used, the flange rotation when it is under internal pressure would be obtained , it is expressed as[9]:

$$\theta_{fP} = \frac{a_1 a_3 b_3 - a_2^2 b_3 - a_3 a_4 b_3 + a_3 a_5 a_6 b_2 - a_3 a_5 a_6 b_1 + a_2 a_6 b_1 - a_2 a_6 b_2}{a_2^2 - 2a_2 a_5 a_6 - a_4 a_6 + a_1 a_6 + a_3 a_4 + a_3 a_5^2 a_6 - a_1 a_3} P \tag{5}$$

The expression of coefficient a and b in the Eq.(5)could be found in appendix of above literature.
When bolted joint components during the operating state, certain bolt deformation under the effect of temperature, pressure and bending moment will be generated, flange bending occurs due to the deformation of bolt. So the flange rotation under bending moment will be obtained, its expression[10] is:

$$\theta_{fM} = \frac{(1-\nu_f^2)M_f V}{LEg_0^2 h_0} \tag{6}$$

The overall flange rotation is the sum of the flange rotation under the function of internal pressure and bending moment, it is expressed as:

$$\theta = \theta_{fP} + \theta_{fM} \tag{7}$$

Through the Eq.(1)(2)(7) to respectively obtain the rotation θ^i and θ^f when it is in the condition of initial tightening and operating.

3. Calculation of gasket deformation and stress

3.1. Establishing deformation compatibility equations

To the statically indeterminate structure of bolted flange connection, that is regarded as a whole,the deformation must have some kind of connection between bolts, flange and gasket.Only the creep of gasket is considered,so deformation compatibility equation is expressed as follows[11,12]:

$$w_b^i + D_g^i + 2w_f^i = w_b^f + D_g^f + 2w_f^f + D_g^c \tag{8}$$

Equation (8) is combined with the bolt force,flange bending moment and gasket axial displacement,the following equation is given:

$$D_g^i - D_g^f - D_g^c = \left(\frac{F_b^f}{K_b^f} - \frac{F_b^i}{K_b^i}\right) - \left(2h_G\frac{M_f^f}{K_{fM}^f} + 2h_G\frac{P}{K_{fP}} - 2h_G\frac{M_f^i}{K_{fM}^i}\right) \tag{9}$$

3.2. The gasket deformation

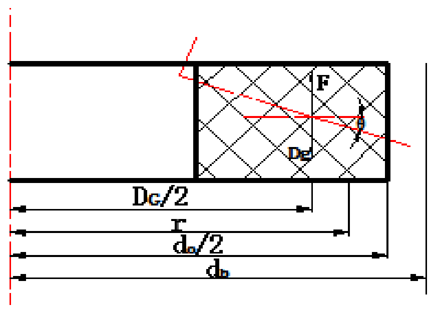

Fig. 4. Gasket deformation model.

In the actual connection, a strong correlation between the flange rotation and the gasket deformation can be established. Relevant data about the above equation is calculated and the curve is described to compared their relationship, from their relationship, it would be found that the flange rotation and gasket stress are coordinated interaction. Gasket contact stress and deformation can be reflected by compressive and resilient performance. Flange bending deformation can be happened due to the effect of the reaction on gasket, flange takes place deflection under internal pressure. And due to the flange deflection, the distribution of gasket stress in the radial direction is not uniform, the separation will be occurred in the inner parts of flange with gasket at this time. So the flange rotation and gasket stress are the main factors that influencing the bolted flange connection system to engender leakage, the seal of bolted flange connection system must set out to be disposed from the flange rotation[13],the gasket deformation and gasket stress. Fig. 4 is the model of gasket deformation.

For any radial position r ,the axial strain of the gasket can be represented as:

$$\varepsilon_c = \varepsilon_G + \frac{(2r - D_G)\tan\theta}{t} \tag{10}$$

The axial deformation of gasket at any radial position r can be expressed as follows[14]:

$$D_g(r) = D_g + (2r - D_G)\tan\theta \tag{11}$$

The axial deformation of gasket can obtained respectively when it is in the state of initial tightening and operating through Eq.(11):

$$D_g^i(r) = D_g^i + (2r - D_G)\tan\theta^i \tag{12}$$

$$D_g^f(r) = D_g^f + (2r - D_G)\tan\theta^f \tag{13}$$

D_g^c is the creep displacement, the performance expression of creep is:

$$D_g^c = D_g^i (B_R + C_R T)\ln t \tag{14}$$

When gasket is in the states of operating and the temperature is 500 °C, the creep of gasket will be generated, so the deformation can be expressed as follows:

$$D_d = D_g^f(r) + D_g^c = D_g^f + (2r - D_G)\tan\theta^f + D_g^c \tag{15}$$

Figure 5 is the curve of compression deformation of the metal flexible graphite composite gasket when the gasket is under operating condition. Owing to the different initial tightening stress that causing the difference of flange rotation, and flange rotation makes the gasket compression levels increase linearly through the radial direction. And when the initial tightening stress reaches 40MPa, 60MPa and 80MPa respectively, the maximal compression deformation of gasket is 0.9386 mm, 1.1842mm and 1.3992mm.Fig. 6 is the curve of gasket deformation at different radial position when the test temperature is 500°C, operating time is 10000h,and internal pressure is 1.35MPa,the same situation can also be reflected in this figure. From the diagram it can be seen that in the inner diameter of gasket, Its amount of deformation gets minimum; in the outer diameter of gasket, the amount reaches maximum, the largest amount of deformation is given by:

$$D_g(d_o) = D_g + (2d_o - D_G)\tan\theta^i \tag{16}$$

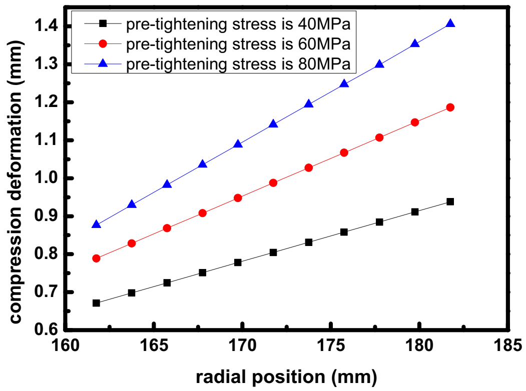

Fig. 5 Compression of gasket at different radial position.

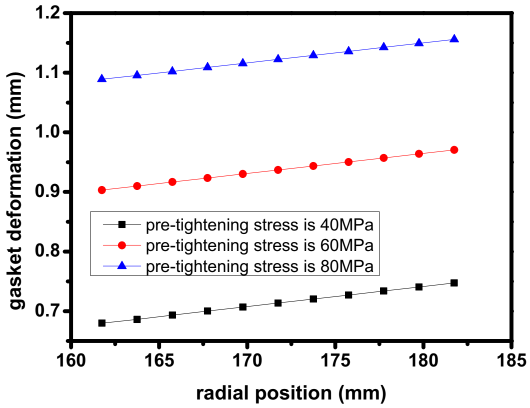

Fig. 6. Gasket deformation at different radial position under the test temperature.

Under the operating conditions, the gasket seating stress can decrease, the resilience of gasket is caused, so the gasket deformation decreases. After creep and resilience of the gasket, when initial tightening stress is 40MPa,60MPa and 80MPa,the maximal gasket deformation is 0.7473 mm,0.9685 mm and 1.1563 mm respectively.

The gasket deformation also can be expressed by time, their relation is given through Eq. (14)and (15):

$$D_d = D_g^f(r) + D_g^i(B_R + C_R T)\ln t \tag{17}$$

In the Fig. 7,the influence of the gasket creep is considered, the relation that gasket deformation changes over time is reflected when the radial position is in the outer diameter of gasket, and under the test temperature of 500 °C,the gasket deformation gradually stabilizes after 10000 h, the curves are described in accordance with the regulation of creep.

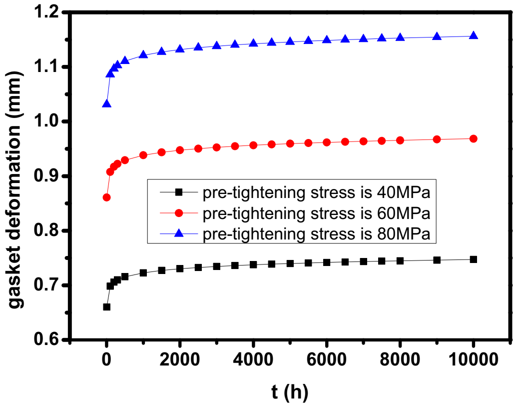

Fig. 7. Gasket deformation changes over time under the test temperature.

3.3. Gasket stress

A good compressive and resilient performance is the key to measure the tightness of bolted flange connections, and the gasket factor m=3.5 and the minimum gasket compression stress y=30MPa could be gained, according to "A High Temperature Performance of Gasket and Its Representation", a series of testing data under high temperature will be got from it. The relationships between gasket deformation and stress are given by Gu and Zhu [15] as follows:

Compressive performance formula is:

$$S^i = \left(A_C - B_C T\right)\left(D_g^i\right)^{N_C} \tag{18}$$

Resilient performance formula is:

$$\frac{S^f}{S^i} = A_S + B_S\left(\frac{D_g^f}{D_g^i}\right)^{(A_T + B_T T)} \tag{19}$$

The following formula can be calculated through the deformation coordination equation (9):

$$\frac{D_g^f}{D_g^i} = 1 - \frac{D_g^c}{D_g^i} - \frac{1}{D_g^i}\left(\frac{F_b^f}{K_b^f} - \frac{F_b^i}{K_b^i}\right) + \frac{1}{D_g^i}\left(2h_G\frac{M_f^f}{K_{fM}^f} + 2h_G\frac{P}{K_{fP}} - 2h_G\frac{M_f^i}{K_{fM}^i}\right) \tag{20}$$

$$\frac{S^f}{S^i} = A_S + B_S\left[1 - \frac{D_g^c}{D_g^i} - \frac{1}{D_g^i}\left(\frac{F_b^f}{K_b^f} - \frac{F_b^i}{K_b^i}\right) + \frac{1}{D_g^i}\left(2h_G\frac{M_f^f}{K_{fM}^f} + 2h_G\frac{P}{K_{fP}} - 2h_G\frac{M_f^i}{K_{fM}^i}\right)\right]^{(A_T + B_T T)} \tag{21}$$

In table 1, A_C, B_C, A_S, B_S, N_C, A_T, B_T are the coefficient of compression regression, B_R, C_R are the creep regression coefficient.

Table. 1 Compression and leakage regression's coefficient of flexible graphite metal gasket.

A_C	B_C	A_S	B_S	N_C	A_T	B_T	A_L	M_L	N_L
287.2	0.465	-0.208	1.114	1.912	7.434	0.001	1.53×10^{-4}	0.681	-0.228

It can be seen that the gasket contact stress is presented in different radial position from Fig. 8.The distribution of gasket contact stress is nonuniform. It is clear to observe the gasket stress is higher when it is closer to the bolt. The flange joint is subjected to the effect of initial tightening force, internal pressure and bending moment, flange ring has a tendency to open in the compaction region. Since a greater compressive deformation occurs near the bolt, the greater gasket stress can be caused at this area. This phenomenon also accords with the description of compressive and resilient performance. Due to the function of flange deflection, the gasket compression stress increases gradually from the inner diameter to the outer one, the whole bolted flange connection system will be crushed when the outer gasket stress is too high and then the leakage behavior takes place. As can be seen from the Fig. 9, the relationship between the residual stress of metal flexible graphite composite gasket and time is represented, gasket residual stress decreases with time increasing within 10000 h, and the smallest residual stress is greater than the minimum seating stress that meeting the requirements of sealing in the operating conditions. The expression (21) is used to inference the relationship about the leakage rate and the corresponding time.

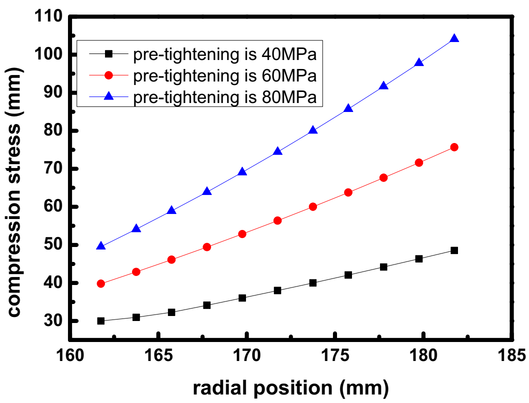

Fig. 8. Relationship between gasket radial position and contact stress.

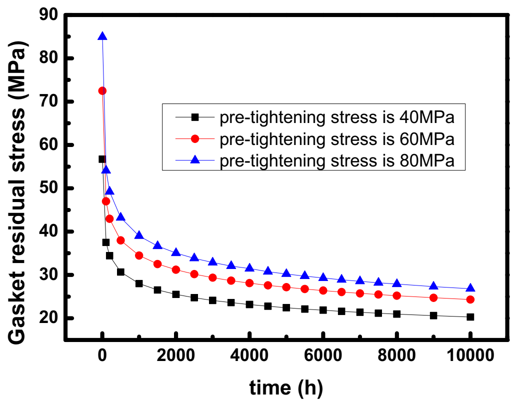

Fig. 9. Relationship curves between gasket residual stress and time.

4. Leakage rate calculate of flexible graphite gasket

Tightness of the bolted flange connection system is represented mainly through its leakage rate. There is a certain relationship between the gasket residual stress and leakage rate by observing a series of experiments, and the tightness of the bolted flange connection system depends largely on the gasket residual stress. The gasket sealing performance is discussed, the relationship between the medium pressure, temperature, and gasket stress can be obtained. For the gasket sealing performance is influenced by medium pressure, temperature and the gasket material, thus realizing the tightness of the bolted flange connection must ensure that the appropriate temperature and gasket stress. Now the expression of the time-dependence leakage rate is [16]:

$$L = A_L P T^{ML} S_G^{\ NL} \tag{22}$$

$$L(t) = 1.422 \times 10^{-2} \times \left\{ S^i \left[-0.208 + 1.114 (1.4699 - 0.01249 \ln t) \right]^{7.984} \right\}^{-0.228} \tag{23}$$

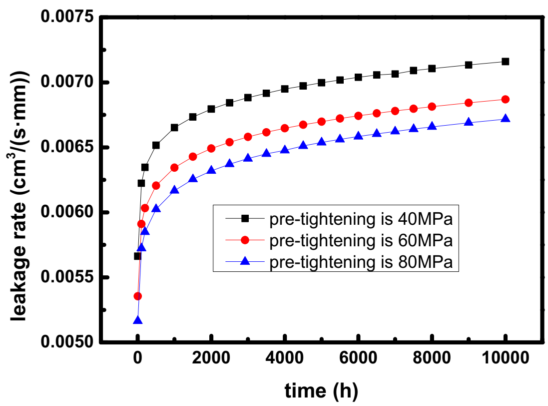

Fig. 10. Relationship between gasket leakage versus time under different conditions.

Figure 10 is the relationship between metal flexible graphite composite gasket leakage rate and time under different conditions. When initial tightening stress reaches 40MPa, 60MPa and 80MPa, the working temperature is 500 ℃,their leakage rate is all in the level from 2.0×10^{-4} to 2.0×10^{-2} .Comparing the data with the table by Lu and Gu ,their level of tightness is standard and economy, the security level Is Ⅰ , the leakage rate is gradually stabilized after 10000h, it reaches the safety level completely of the bolted flange connection system. Combined with Fig. 9 and Fig. 10 respectively show that the time-dependence about the gasket residual stress and the leakage rate. And the outer diameter of gasket compression is the highest, thus its effect on the gasket leakage rate is more important.

5. Conclusion

Analyzing the tightness of the bolted flange connection system, the primary conclusions could be achieved:

(1) The correlate of flange rotation, gasket deformation and the gasket contact stress were studied systematically, using the relationship to deduce the flange rotation and gasket stress are the main factors that affecting the tightness of the whole system.

(2) The metal flexible graphite composite gasket has good temperature resistance and sealing performance, and the gasket stress increases linearly from inner to outer diameter due to flange rotation and gasket deformation, so when the outer gasket stress is too high, the serious deformation will be generated, and the leakage is caused.

(3) In the process of operating, gasket will produce partial resilience, but under the effect of high temperature, the creep of gasket will be appeared. When the phenomenon of creep is more sharp, the resilient rate will decline. From the analytical result can know that the effect of creep on the tightness of bolted flange system is small.

(4) Based on the theory of tightness, the leakage rate is calculated. They are all in the secure scope of the tightness in the corresponding time. On the basis of considering the creep effect of gasket, their tightness is standard and economic.

Acknowledgements

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